# THE DEVELOPMENT OF A 1 KW DIRECT METHANOL FUEL CELL SYSTEM

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We are nearly finished building a 1 kW net output direct methanol fuel cell demonstration system to address automotive applications. It is entirely self contained and computer controlled. It will operate at $25^0C - 40^0C$ at 0% - 100% relative humidity.

The fuel cell stack will be capable of delivering 1300 watts and contain 70 cells. Three hundred watts are required to power ancillary devices needed for a full system. It will operate on .5 M to 1 M methanol at $60^0C$. To date we have validated the stack design by successfully demonstrating a 20 cell stack.

The system was designed to achieve four major goals. The first was maintaining an adequate thermal and water balance, the second was insuring that the weights and volumes of all ancillary components are minimized, the third was minimizing ancillary power consumption, and the fourth was minimizing stack size to the extent this was consistent with the first three items. Critical to the realization of these goals is a new concept in compact heat exchanger design that allows the construction of a very small and light-weight condenser.

## INTRODUCTION

At the Jet Propulsion Laboratory in Pasadena, we have been developing a direct methanol fuel cell (DMFC) technology for about 11 years[1]. Until recently, the primary focus of our work has been the development of small fuel cells for military applications[2].

The DMFC system also has automotive applications. Because these applications generally require power on the order of 50 kw or more, much larger fuel cell systems are required. In order to address the kinds of issues associated with such systems we are building a 1 kw net output demonstration system for the SCAQMD and the CARB, two environmental agencies for the State of California. This system is entirely self contained (all balance of plant components draw power from the stack), and is controlled by a computer. The computer serves to maintain system temperature, insure water balance, and monitors all cells to detect malfunction.

# STACK

DMFC stacks have one characteristic in common; they tend to accumulate water at the cathode. This water is mostly brought by electroosmosis from the anode as a consequence of the large amount of water present in the fuel. Some water is also generated in-situ by the cathode reaction. There is also a small amount of water that reaches the cathode by simple diffusion. Removing the water is very important to proper functioning. The method of removal has significant consequences with respect to system design.

To date we have implemented three approaches to address this issue. The last of these represents the design philosophy chosen for this system. The first and most simple requires a lot of energy. In this design, the flowfield air flow channels are small and the stack is internally manifolded. Water is blown out by supplying cathode air at pressures up to 100 torr. The design advantage is that the biplates can be quite thin and the resulting stack very compact. The pressure requirement necessitates the use of an air pump with the consequent consumption of considerable power. The parasitic losses attributable to the pump are unacceptable.

The second style of stack is internally manifolded on the methanol side and externally manifolded on the air side. It operates at low pressures of less than .1 torr. At these pressures, a fan can be used for the air source; its power consumption is minimal. This low pressure drop is achieved by increasing the size of the flow channels in the biplate so that gravity alone can drain the water, and externally manifolding the cathode chambers of the stack. In the externally manifolded design, biplates are open on two of their four narrow edges. The openings are lined up when the stack is assembled. An air manifold is then attached to the side of the stack. Using the manifold, air is then blown through the openings in the side of the stack. An exhaust manifold is usually attached to the other side of the stack. The air manifolds are oriented vertically so that water drainage under the influence of gravity is possible.

This design approach works well, but is not suited to larger stacks. In order to maintain the extremely low pressure drop needed to allow a simple fan to be used as an air source, the manifolds have to be quite large. Plumbing a large system becomes impractical, and results in excessive system volume.

The design approach for our new stack was a hybrid of the two approaches just described. It was designed and built under contract with Giner Electrochemical Systems LLC. We used a totally internally manifolded design but with a very open flow channel structure. Gravity drains the flowfield, but water is blown out of the manifold by pressure. This approach resulted in a stack with a pressure drop of less than 10 torr. This is considerably higher than the second design, but much lower than the first. To provide air at this pressure, a multi-stage blower is required. This device is essentially a collection of staged fans. A blower is less power consuming than a pump of equivalent flow capability. Using the hardware built for the 70 cell stack, a 20 cell short stack has been built to demonstrate the design concept. A picture of this stack is shown below in Fig.1. Each cell is intended to operate at .4 V and 140 ma/cm$^2$. The 20 cell stack should deliver 8 V at that current density. The plot of stack performance is shown in Fig. 2. It reveals that the actual performance falls a bit shy of this mark, but not by much. We believe that there will be no scale up issues going from the 20 cell stack to the 70 cell stack.

Table 1 below gives the essential characteristics of the stack. Note 268 Watts of out put are held in reserve against possible underperformance. Hence, the "1300 Watt Stack" is actually designed to put out 1568 Watts.
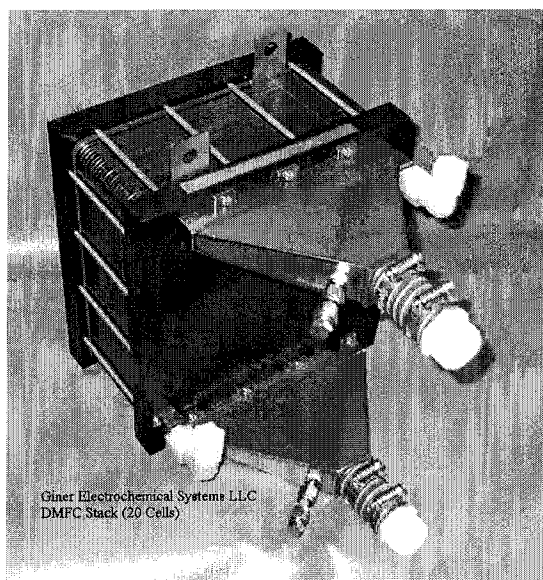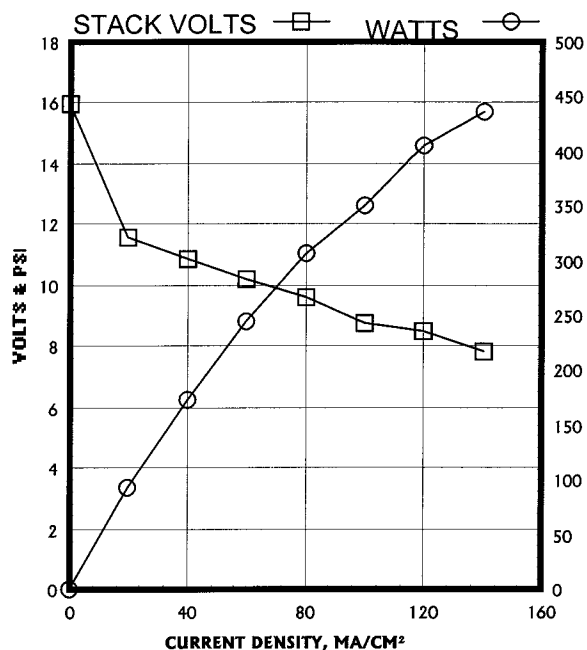
Fig. 1 20 Cell 440 Watt Stack



Fig. 2 Performance of 20 cell stack

•OPERATING TEMPERATURE $60^0C$
•70 CELLS
•1568 WATTS
•AIR FLOW RATE 315 liter/min (11.1 cfm)
    —AIR FLOW RATE IS APPROX. 3.25 STOKE (CROSSOVER INCLUDED)
•PRESSURE DROP < 10 torr
•FUEL FLOW RATE 14-17.5 liter/min   (3.7-4.6 gpm)
•ACTIVE CELL AREA 400 $cm^2$  (62 $in^2$ )
•STACK DIMENSIONS 9.7" X  10.2" X 13.75" (24.6 cm x 25.9 cm x 34.9 cm)
INCLUDING ENDPLATE
•BIPLATE 22.86 cm x 24.1 (9" X 9.5")
•VOLUME 19.3 liter  (.68 $ft^3$ )
•WEIGHT 26 kg (57.3 lb)
•**CURRENT DENSITY 140 ma/$cm^2$ @ .4 V (CROSSOVER ~ 32ma/$cm^2$)**
•60 watt/kg
•81 watt/liter

Table 1.  Stack Characteristics 70 Cell Stack

## SYSTEM FEATURES

We are nearly finished constructing a fuel cell system designed to operate with air supplied to the stack at atmospheric pressure. This system will have a 70 cell stack. A schematic diagram of the system is shown in Fig. 3. The weights of all components are given in Table 2. It allows for maintenance of constant stack temperature, water balance, and fuel methanol concentration. This system schematic does
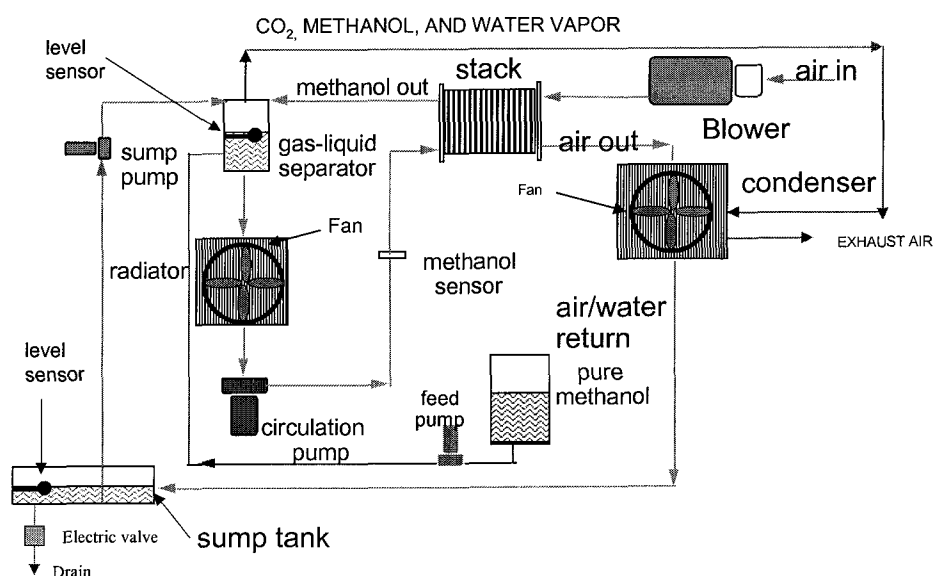


**Fig. 3. Schematic of 1 KW Direct Methanol Fuel Cell System**

FUEL NOT INCLUDED     TOTAL 68KG (150 lb)    STACK 26 KG (57.3 LB)

RADIATOR  6.45 KG (14.2 LB)
CONDENSER 7.5 KG (16.5 LB)
STACK BLOWER AND DRIVE UNIT 2.27 KG (5 LB)
RADIATOR FAN 1.54 KG  (3.4 LB)
CONDENSER FAN .82 KG (1.8 LB)
COMPUTER 3.0 KG (6.6LB)
DATA ACQUISITION AND CONTROL ELECTRONICS 2.18 KG (4.8 LB)
DILUTE METHANOL PUMP 1.18 KG (2.6 LB)
PURE METHANOL METERING PUMP AND DRIVE UNIT .56 KG (1.2 LB)
STARTUP BATTERIES 1.27 KG (2.8 LB)
LEVEL SENSORS .04 KG (.09 LB)
PURE METHANOL TANK .43 KG (.95 KG)
SUMP TANK .24 KG (.53 LB)
GAS LIQUID SEPARATOR (TANK) 1KG (2.2 LB)
PURE METHANOL 4 HOURS OPERATION 5.2 KG (11.5 LB)
DILUTE FUEL IN GAS LIQUID SEPARATOR 8 KG (17.5 LB)
FITTINGS, TUBING AND ODDS AND ENDS 5 KG (11 LB)
METHANOL SENSOR AND ELECTRONICS 500 GM (1.1 LB)

**Table 2.  Weights of  all Components**

not show a DC-DC converter, the computer controller, or the cold start battery and battery charger.

The DC-DC converter takes power from the stack and delivers it at constant specified voltage to all system components. The computer turns on and off components as needed and monitors all cells in the stack for possible malfunction. Detection of malfunction results in immediate system shutdown. The cold start system consists of lithium ion batteries and a charger that is powered by the stack. Both batteries and charger are integral to the laptop computer used as a controller.

There are three major systems shown in Fig. 3. The fuel delivery system, the air delivery and water recycling system, and the temperature control system. The fuel delivery begins with a pure methanol tank. The feed pump meters pure fuel into the gas liquid separator which doubles as a dilute solution reservoir. The dilute (.5 – 1 M) solution is circulated through the stack and radiator and gas liquid separator by the circulation pump. A methanol sensor in the loop detects concentration changes. This sensor signals the computer which then activates the feed pump to maintain homeostasis.

The methanol sensor is a device previously developed by my colleagues at JPL[3]. It measures methanol by detecting the rate of methanol oxidation under diffusion control at a fuel cell anode. The current is proportional to the concentration. This is shown in Fig. 4 below.
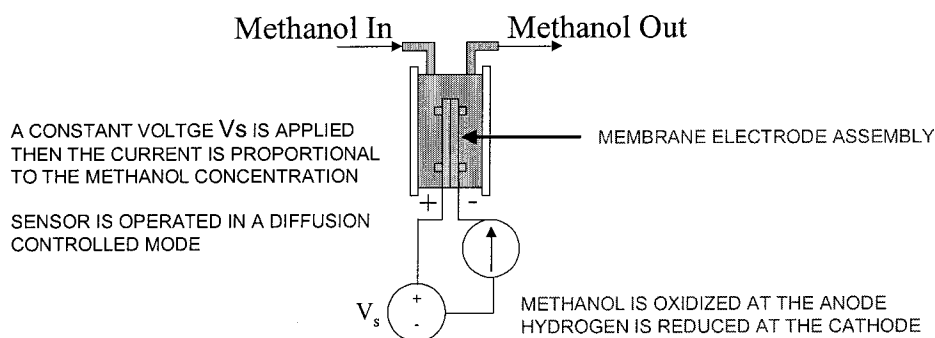


**Fig. 4. Methanol Concentration Sensor**

The dilute fuel passes through a radiator shown in Fig. 3. This radiator is part of the temperature control system, it dissipates excess heat generated by the stack. The radiator fan is turned on and off by the computer in order to keep the dilute fuel loop temperature constant. Because the dilute fuel runs through the stack this controls the temperature of the stack as well.

The air delivery system and water recycling system consists of a blower to provide air to the stack, a condenser to remove water vapor from the stack exhaust, and a sump tank and pump to collect water from the condenser. Condenser water is a mixture of condensate and water that was already liquid when it left the stack. A sump pump returns collected water to the gas liquid separator to make up for water lost. A level sensor in that tank terminates pumping to prevent overfilling. The sump tank also has a level sensor to prevent overfilling. When it is tripped, the electric drain valve dumps excess water.

THERMAL ANALYSIS

Our thermal analysis is designed to insure two things. First we must be certain that the excess heat generated by the stack can be dissipated, second we must insure that

the heat generated is sufficient to maintain operating temperature. In effect, this defines two sets of operating extremes that the system must be capable of handling. In our system the major heat sink is the radiator, and evaporative cooling at the cathode. The minor one is plumbing, stack surface, tanks etc. The two operating extremes are defined by the conditions below and were the projects design goals.

1. $40^0$C ambient temperature, 100% relative humidity.
2. $25^0$C and 0% relative humidity.

The first condition defines the minimum size of the radiator. At 100% relative humidity, there can be no evaporative cooling. Also the radiator must be sized to deal with the relatively low delta T ($20^0$C) between the stack temperature of $60^0$C and the environment. At 26% efficiency, a stack with 1568 watts of output produces 4460 Watts of heat. If the radiator is sized at 4000 Watts, there will be sufficient cooling capacity if the rest of the system is not insulated. Those losses will account for between 416 Watts and 1664 Watts.

At the other extreme, overcooling of the stack by evaporation can occur at the cathodes. Because evaporation is a function of air flow rate and stack temperature, cooling sets an upper limit on both. Choosing an appropriate operating temperature and air flow rate is an iterative process because the flow rate changes with choice of temperature. Instead we will show that the $60^0$C operating temperature is a is a good one, and what happens to the magnitude of the evaporative heat losses as the temperature rises within narrow limits unlikely to affect the required air flow rate significantly. This information is presented in Fig. 4 below.

It is clear from Fig. 4 that at ~$72^0$C evaporative cooling (at 0% relative humidity) alone could remove all the heat the stack produces. This is the highest practical operating temperature. Operation under these conditions would require the system to be well insulated. This would increase system complexity and volume.
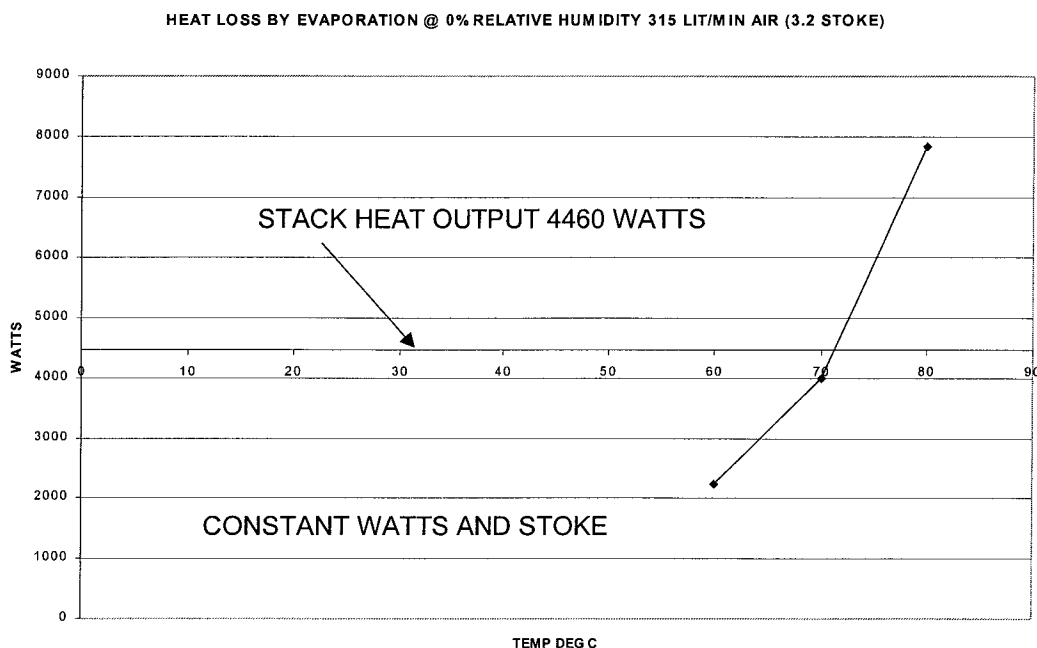
HEAT LOSS BY EVAPORATION @ 0% RELATIVE HUMIDITY 315 LIT/MIN AIR (3.2 STOKE)



Fig. 4 Heat Loss by Evaporative Cooling

## WATER BALANCE

Water is generated by the electrochemical reaction at the cathode as well as from the chemical oxidation of methanol that unavoidably "crosses over" from the anode to the cathode when Nafion is the polymer electrolyte membrane. Water losses occur by evaporation at the cathode of the fuel cells. Some liquid water is also released from the cathode chambers of the stack, but 100% of this is easily recycled.

A portion of the water vapor can be recycled by the use of a condenser. Some is unavoidably lost because the condenser cannot cool the stack exit stream to below the ambient temperature. If we make the reasonable assumption that the condenser exhaust is $5^0C$ above ambient we can calculate the water balance (net loss or gain) over a range of temperatures. This is shown in Fig. 5. As expected, this is highest for the condition of $40^0C$ ambient temperature at 0% relative humidity. It is clear that at that temperature (our maximum operating temperature) there is a net loss of water from the system. It can be shown that this can be made up by replacing pure methanol in the fuel tank by a solution containing 25% water. At $34^0C$ and 0% relative humidity Fig. 5 shows that the system is in water balance. Pure methanol can again be used as a fuel. Naturally, at higher relative humidity, water balance can be achieved at higher temperatures.

## CONDENSER

A condenser capable of cooling the $60^0C$ exhaust stream of the stack to $45^0C$ at $40^0C$ ambient and an air flow rate of 360 liter/min must have a capacity of 1335 Watts. This poses quite a problem because conventional condensers capable of operating with only a $20^0C$ temperature difference between the ambient temperature and the process stream are generally bulky and heavy. An 800 Watt tube and fin condenser we purchased and shown in Fig. 6 had a cooling capacity of 19.3 watts/liter and 59 watts/kg. Assuming linearity, a condenser of the capacity required would require 69 liters of space and weigh 23 kilograms. This is unacceptable. An entirely new concept in condenser design is clearly required. To this end JPL collaborated with MER Corp. to design a custom made condenser using their proprietary polycapillary[4] matrix technology.
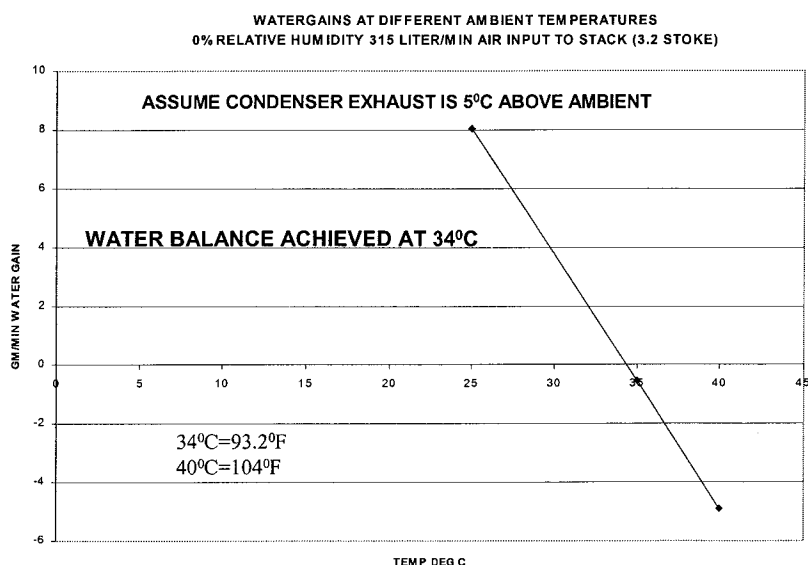
WATERGAINS AT DIFFERENT AMBIENT TEMPERATURES
0% RELATIVE HUMIDITY 315 LITER/MIN AIR INPUT TO STACK (3.2 STOKE)



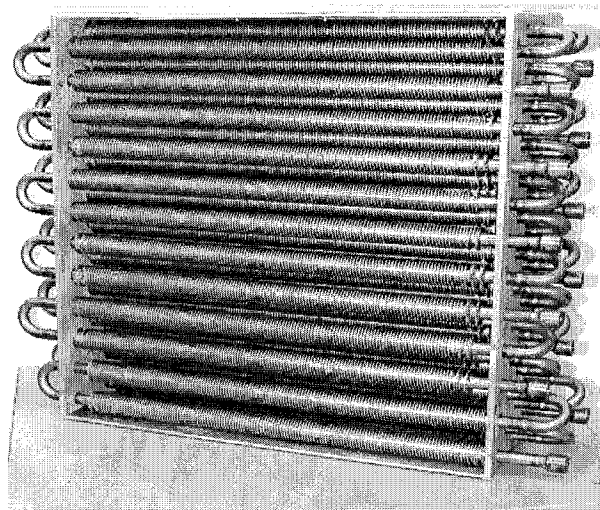**Fig. 5 Water Gain and Loss vs Temperature**

**Fig. 6 Conventional Tube and Fin Condenser**

This technology permits a drastic weight and size reduction. A unit was designed that weighs 7.5 kg and has a volume of 11 liters. It has an estimated capacity of 2000 watts. This drastic reduction in size and weight is made possible by polycapillary heat exchange elements shown in Fig. 7.
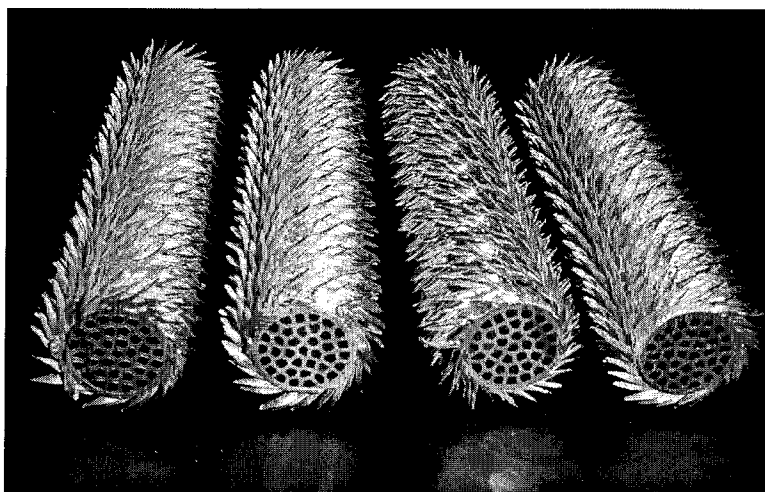


**Fig. 7 Polycapillary Heat Exchange Elements**

In a tube and fin arrangement the cooling air exchanges heat with high surface area fins, but the condensing stream exchanges heat with a low surface area tube. The polycapillary heat exchange elements provide high surface area to both streams. This increases heat transport dramatically. The capillaries shown in Fig. 7 carry the cooling air, while the condensing stream passes over the high surface area "ribbons" attached to the outside of the element.

An additional weight saving is achieved by making these elements out of aluminum and chrome plating them to prevent corrosion. Corrosion may occur because of the acidifying effect of $CO_2$ generated by chemical oxidation of "crossed over" methanol at the cathode. By contrast, the tubes in a tube and fin condenser had to be

made out of stainless steel because it was not practical to chrome plate the inside of the tubes.

The poly capillary tubes are assembled into a condenser shown in Fig. 8. The condensing stream flows in through the large port at the narrow side of the condenser. The cooling stream enters normal to the wide side.
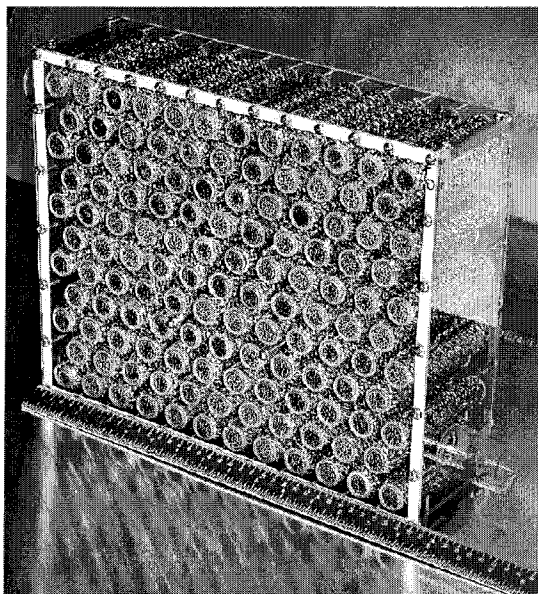


**Fig. 8    Polycapillary Matrix Condenser**

This condenser provides us with some other more subtle advantages. It requires a much smaller cooling fan. Not only does this reduce the additional weight and volume associated with that component, it also decreases power consumption from >100 watts to about 38 watts. This single change is responsible for a 17% decrease in parasitic power loss related to balance of plant power consumption.

## CONCLUSIONS

We have demonstrated that it is possible to design a 1 KW net output direct methanol fuel cell system that will operate at ambient pressure and can be maintained in thermal and water balance. This is done by choosing an appropriate operating temperature, fuel concentration and properly designed heat exchangers. In addition, we have shown a number of advances in technology. These include a low pressure stack design with good water management capabilities, a breakthrough in condenser design, and a feedback controlled fuel delivery system using a methanol concentration sensor previously developed by colleagues at JPL.

## ACKNOWLEDGEMENTS

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